Robone: Next Generation Orthopedic Surgical Device

(Seminar Presentation)

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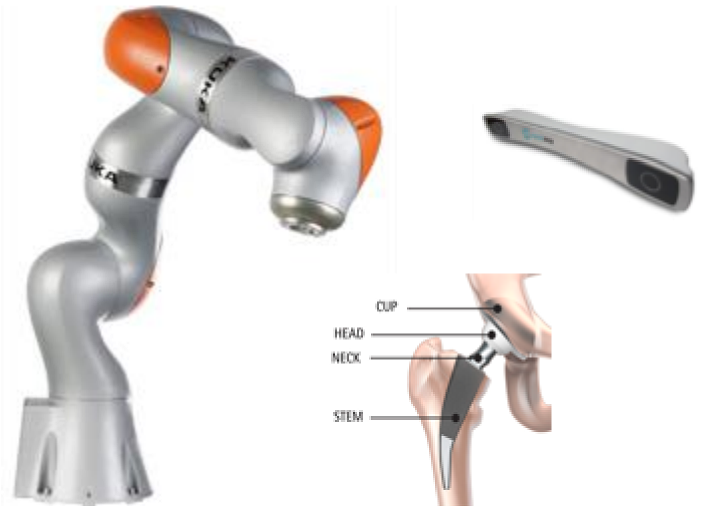


Overview

- Project summary
- Background
- Selected paper
- Importance
- Theory
- Simulation
- Results and assessment
- Conclusion

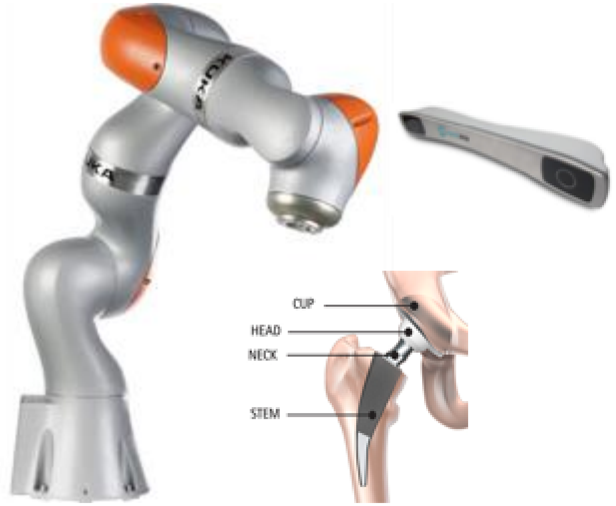
Project Summary

Hip replacement surgery is one of the most common orthopedic suregries

A next generation system will make real time position adjustments using a device such as an optical tracker so fixation is no longer necessary

Robot arm is used to cut the shape of the implant through the bone, then the implant is inserted

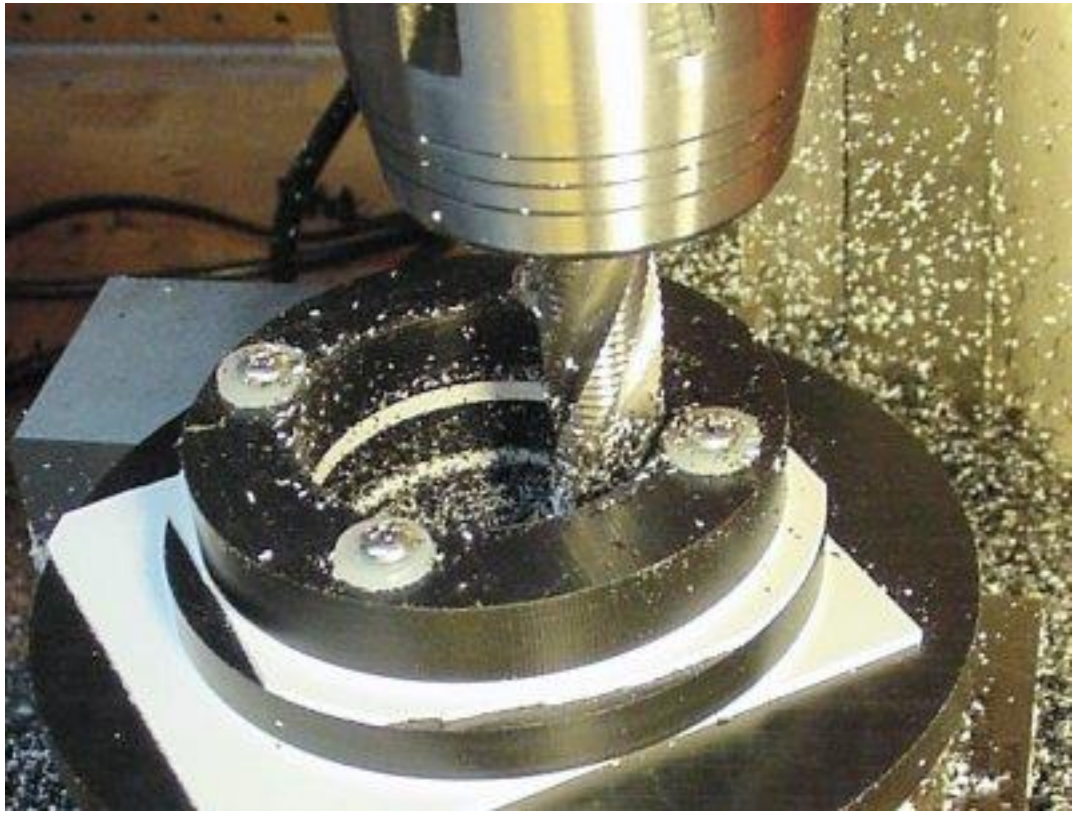
Cutting through the bone requires a milling device attached to the arm



http://en.wikipedia.org/wiki/Hip_replacement

Background

- Milling is the process of removing material using a rotary cutter
- Widely used in industry and other applications machining material to proper size and shape
- Also used in hip replacement surgery
  - Cutting the implant shape through the bone



http://www.thetoolanddieguy.com/category/the-basics-milling/

Background

- Bone is a nonhomogeneous material
  - Its properties varies with location
- Possible damage to the cutting tool and the bone
  - If cutting speed is set to improper value when tool drag varies unpredictably

https://depts.washington.edu/bonebio/ASBMRed/structure.html

Chosen Paper

Nonhomogeneous Material Milling Using A :Robot Manipulator With Force Controlled Velocity

J. Zuhars and T. C. Hsia

Department of Electrical and Computer Engineering University of California Davis

Importance

- The milling speed is limited by
  - maximum applicable force at the tool tip
  - the hardness of the material being removed

- Exceeding the maximum allowed speed would cause tool chattering
  - damage to the tool and the workpiece

- An overall safe constant speed is practical but is not efficient in cutting time

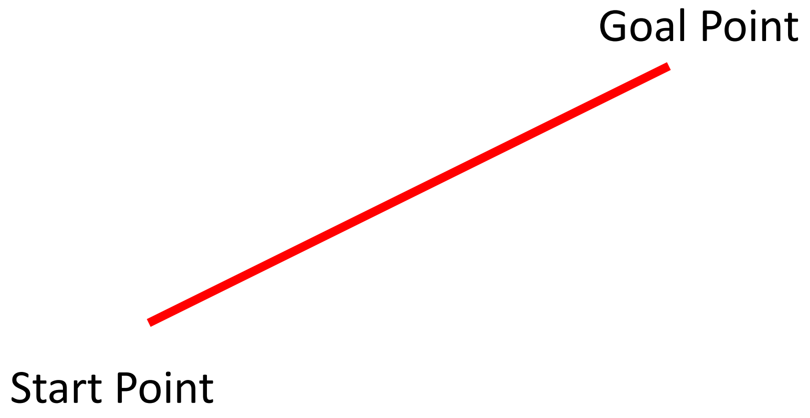
- Bone densities are nonhomogeneous, and the degree of hardness and location of this material cannot be known beforehand for a particular bone

Importance

- Design of a Force Controlled Velocity (FCV) algorithm for a milling robot manipulator
- FCV milling robot will automatically adjust the cutting velocity so that the tool slows down while cutting through high force producing material and speeds up during low force cutting
- The main idea of FCV is to use the sensed force to modify the velocity profile of the tool trajectory

High Sensed Force ↑ : Reduce Velocity ↓

Low Sensed Force ↓ : Increase Velocity ↑

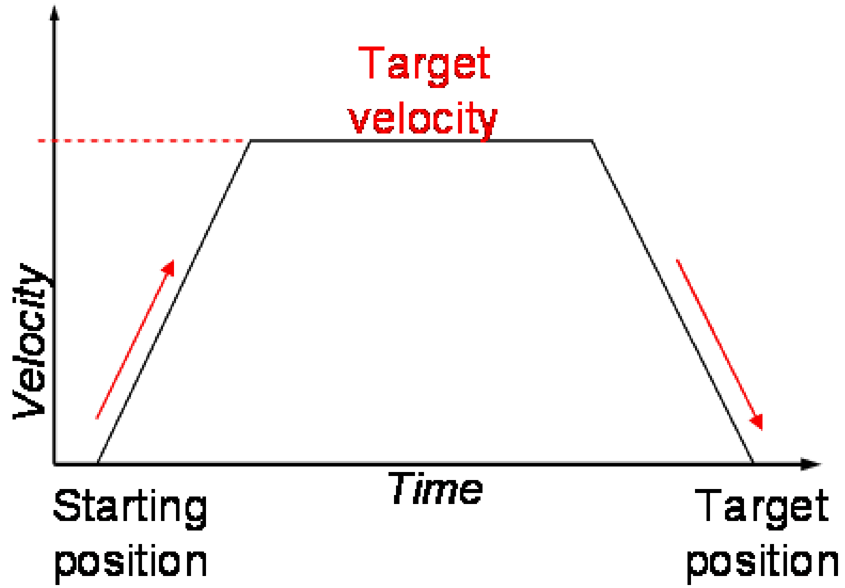


Theory

- Straight line motion trajectory planner with a real time set point generator to implement Cartesian motion

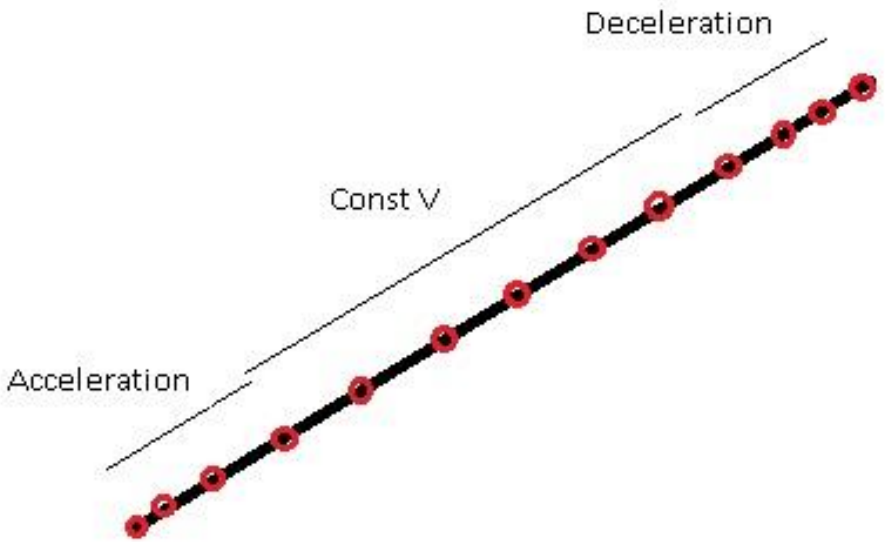
- Input
  - Cartesian goal position
- Output
  - calculates a three motion phase parameter set for each Cartesian axis

- The three motion phases are the acceleration, constant velocity, and deceleration phases.



Motion Planning

$$P(t) = P_0 + V_0 (t - t_i) + \frac{1}{2} A (t - t_i)^2$$



- whereP_0, V_0 and A are the planned initial position, initial velocity, and acceleration for each axis and motion phase, and t_i is the initial time for each phase.

Delay Function

- Replacing elapsed time with a function of elapsed time and force

$$T = t - D(t, F(t))$$

$$
\begin{aligned}
P(T) &= P_o + V_o\,(T - t_i) + \frac{1}{2} A\,(T - t_i)^2 \\
&= P_o + V_o\,(t - D(t, F(t)) - t_i) + \frac{1}{2} A\,(t - D(t, F(t)) - t_i)^2
\end{aligned}
$$

Delay Function

- The experience of the bone milling application suggests that this function should affect velocity the least when tool tip force is low and should cause the velocity to approach zero as force approaches some maximum value

$$T = t - D(t, F(t))$$

$$\frac{d}{dt}T = 1 - \frac{d}{dt}D(t, F(t))$$

- This would be the condition:

$$0 < \frac{d}{dt}D(t, F(t)) < 1$$

Nonlinear Delay Function

- During an FCV milling procedure, it is desirable for velocity variations to be less sensitive to force variations at low force magnitudes than at high force magnitudes
- Ease of analysis

$$0 < \frac{d}{dt} D(t, F(t)) < 1$$

$$\frac{d}{dt} D(t, F(t)) = e^{-R(MaxForce - F(t))}$$

Tool Force Model

- The tool base is defined as where the tool attaches to the force sensor
- Tool tip force model that depends on environmental drag and tool velocity.
- The force measured at the tool base can be modeled using Hooke's Law

- $Ftt(t)$: force on the tool tip
- $\sigma(t)$: observed drag coefficient
- $X(T)$: tool tip position in
- $F(t)$: force at the tool base
- $P(T)$: tool base position
- K: tool spring constant

$$F_{tt}(t) = \sigma(t)\, dX(T)/dt$$

$$F(t) = K\,(P(T) - X(T))$$

$$F_{tt}(t) \doteq F(t)$$

Tool Force Model

- Combining the equations in the previous slide

$$\frac{d}{dt}F(t) = K\,V(T) - K\,\frac{F(t)}{\sigma(t)}$$

$$F(t) = K\,e^{-K\int \sigma(t)^{-1}\,dt} \int e^{K\int \sigma(t)^{-1}\,dt}\,V(T)\,dt$$

Tool base position model

- In the second phase of motion

$$P(T) = V_o\,(t - D(t, F(t)))$$

$$P(T) = V_o \times \left[t - \int e^{-R(\text{MaxForce} - Ke^{-K\int \sigma(t)^{-1}dt} \int e^{K\int \sigma(t)^{-1}dt} V(t)dt)} dt \right]$$

- Later, this is the key equation for the simulation verification:

$$\frac{d}{dt}V(T) = (R\,K\,(V_o - V(T)))\,(\sigma(t)^{-1}\,(\text{MaxForce} + R^{-1}\,\text{Ln}\,(1 - V_o^{-1}\,V(T))) - V(T))$$

Simulation

- Analyzing the FCV method from a simulated performance perspective
- Solves numerically for the tool velocity, acceleration and position using equation below

$$\frac{d}{dt}V(T) = (R\,K\,(V_o - V(T)))\,(\sigma(t)^{-1}\,(MaxForce + R^{-1}\,Ln\,(1 - V_o^{-1}\,V(T))) - V(T))$$

Simulation

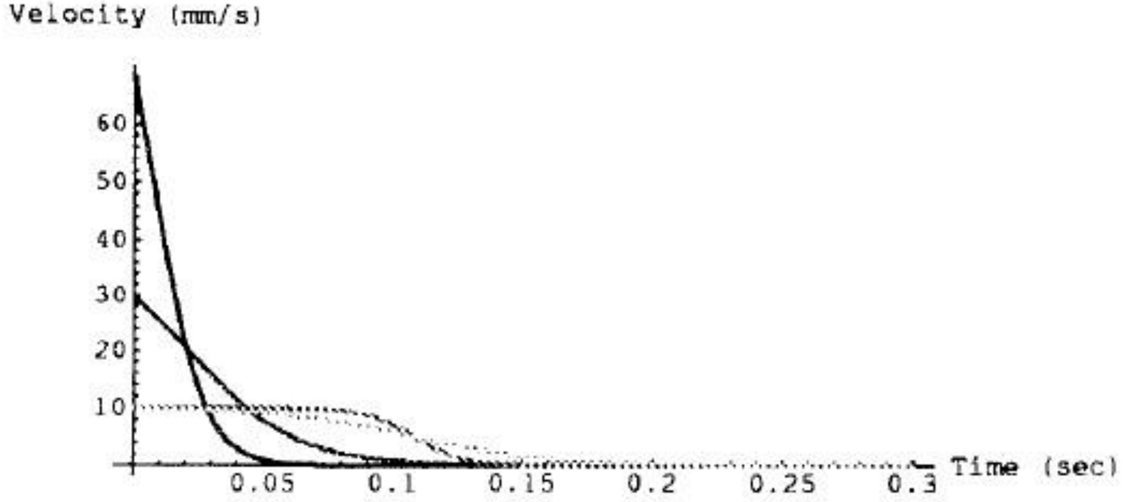
- Two cutting scenarios
  - Uncuttable Object Contact
    - Tool hitting an uncuttable object while traveling through air at max velocity
  - Variable Drag Contact
    - Drag profile including steps, ramps and sinusoids

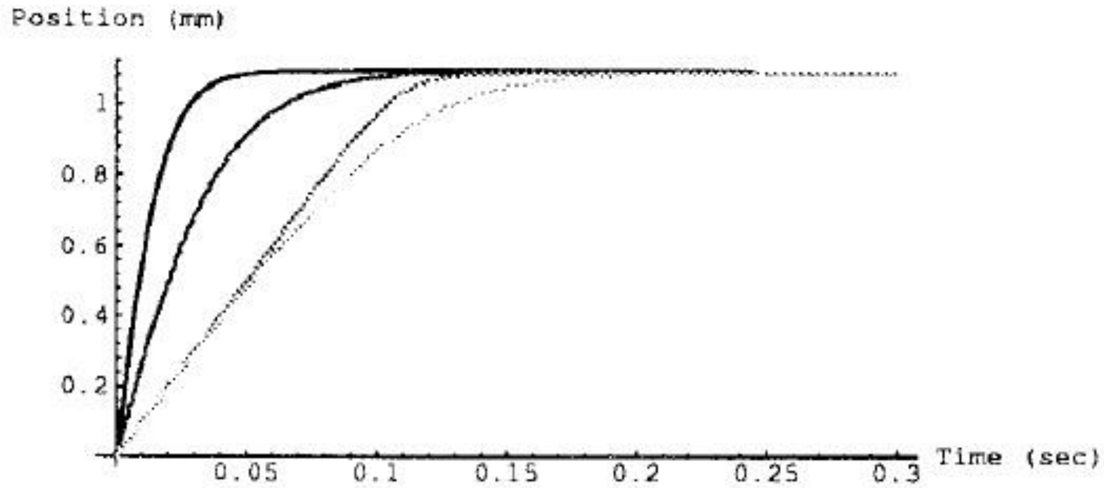
Table 1. System Parameters Used in Simulations

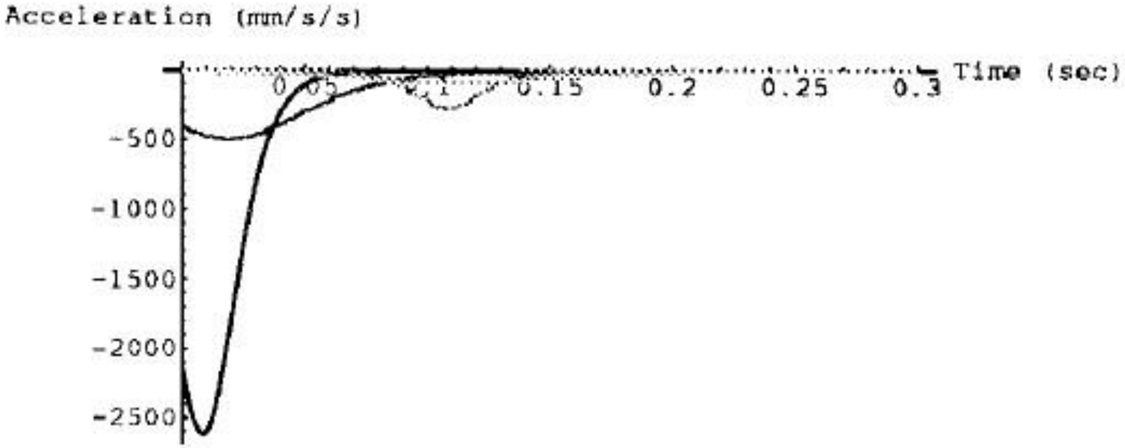
CASE		K (N/mm)	Max F (N)	DMax (mm/s^2)	V_o (mm/s)	V_{Max} (mm/s)	R
1	Optimal V_o, V_{Max}	10.2	11.12	2620	95.35	68.21	0.113
2	Optimal V_o, V_{Max}	10.2	11.12	500	41.65	29.80	0.113
3	Constrained V_o, V_{Max}	10.2	11.12	275	10.00	10.00	1.078
4	Constrained V_o, V_{Max}	10.2	11.12	100	9.87	9.87	0.392

Results

- Uncuttable Object Contact
  - Velocity and Position plotted with elapsed time

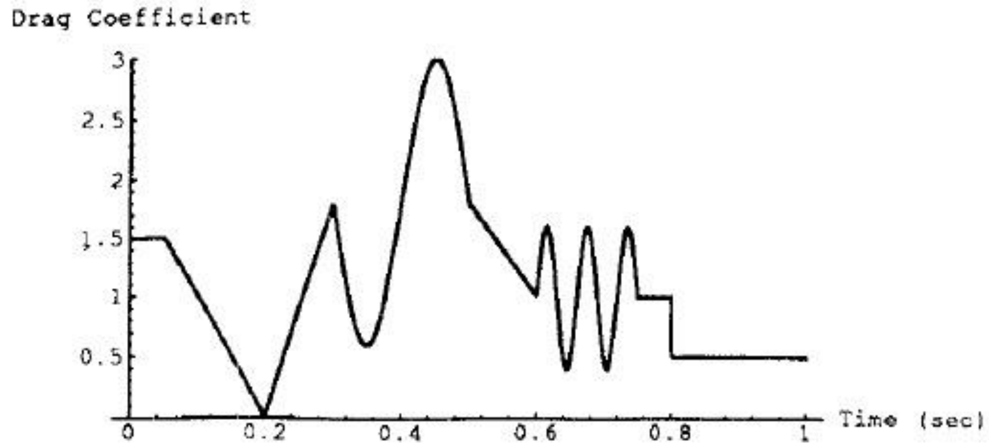


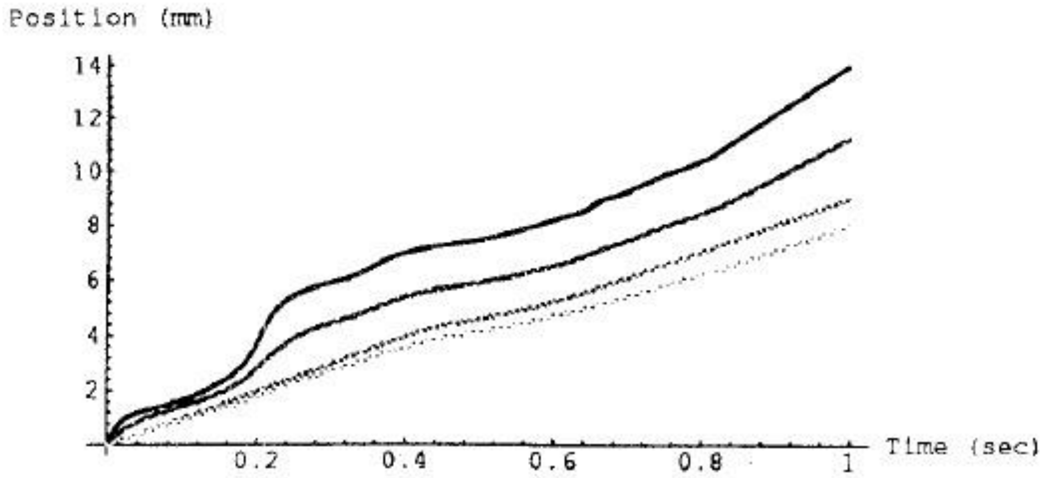


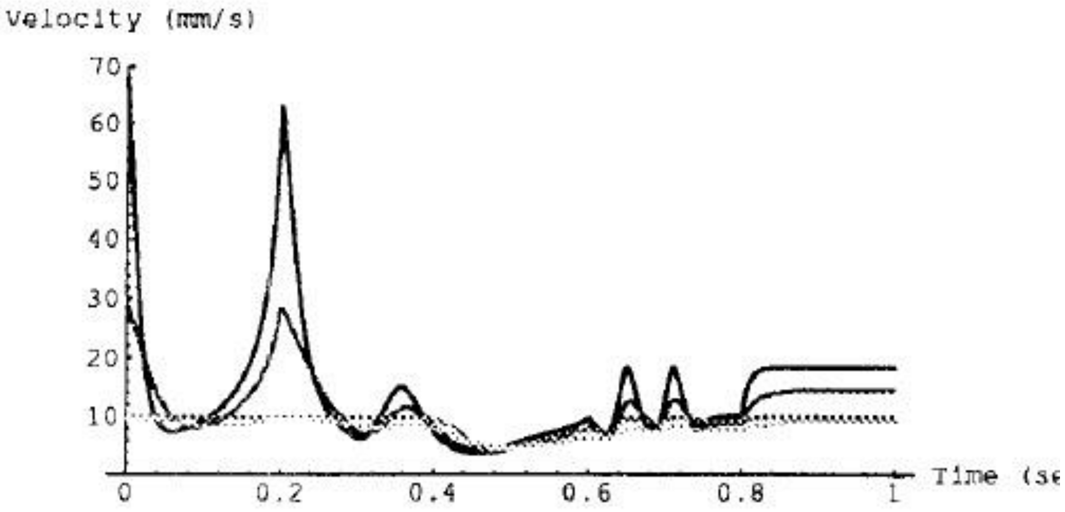


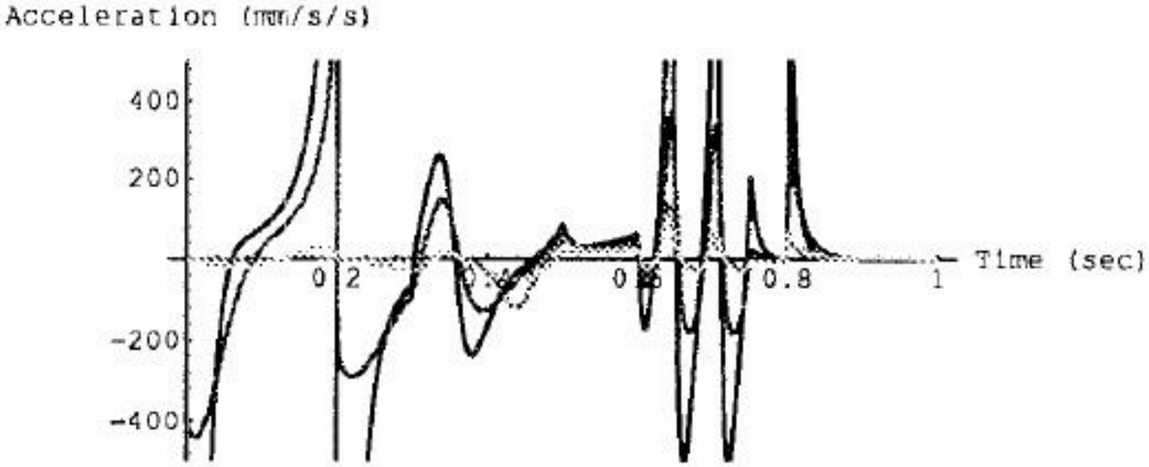
Results

- Variable Drag Contact
  - Velocity and position plotted with elapsed time









Assessment

- What I liked…
  - FCV algorithm for cutting nonhomogeneous materials
  - Novel and efficient design of time delay function
  - Thorough theoretical analysis of the algorithm
  - Assumptions to simplify the equations

- What could have been better…
  - Little detail on the simulation verification
  - Lack of thorough discussion on the simulation results
  - Lack of experimental verification

Conclusion

- A great algorithm for modifying the trajectory velocity profile was proposed
- Simulation results verified the efficiency of the algorithm
- Possibility of implementing a similar algorithm into our project
- Milling was originally planned in max goals
    - Cancelled due to time limits for class project
    - Will be done after the semester

Questions?